

User Cooperation in Wireless Powered Communication Networks

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Abstract—This paper studies user cooperation in the emerging wireless powered communication network (WPCN) for throughput optimization. For the purpose of exposition, we consider a two-user WPCN, in which one hybrid access point (H-AP) broadcasts wireless energy to two distributed users in the downlink (DL) and the users transmit their independent information using their individually harvested energy to the H-AP in the uplink (UL) through time-division-multiple-access (TDMA). We propose user cooperation in the WPCN where the user which is nearer to the H-AP and has a better channel for DL energy harvesting and UL information transmission uses part of its allocated UL time and DL harvested energy to help to relay the far user's information to the H-AP, in order to achieve more balanced throughput optimization. We maximize the weighted sum-rate (WSR) of the two users by jointly optimizing the time and power allocations in the network for both wireless energy transfer in the DL and wireless information transmission and relaying in the UL. Simulation results show that the proposed user cooperation scheme can effectively improve the achievable throughput in the WPCN with desired user fairness.

I. INTRODUCTION

Energy harvesting has recently received a great deal of attention in wireless communication since it provides virtually perpetual energy supplies to wireless networks through scavenging energy from the environment. In particular, harvesting energy from the far-field radio-frequency (RF) signal transmissions is a promising solution, which opens a new avenue for the unified study of wireless energy transfer (WET) and wireless information transmission (WIT) as radio signals are able to carry energy and information at the same time.

There are two main paradigms of research along this direction. One line of work aims to characterize the fundamental trade-offs in simultaneous WET and WIT with the same transmitted signal in the so-called simultaneous wireless information and power transfer (SWIPT) systems (see e.g., [1]–[3] and the references therein). Another line of research focuses on designing a new type of wireless network termed wireless powered communication network (WPCN) in which wireless terminals communicate using the energy harvested from WET (see e.g., [4]–[6]).

In our previous work [6], we have studied a typical WPCN model, in which a hybrid access-point (H-AP) coordinates WET/WIT to/from a set of distributed users in the downlink (DL) and uplink (UL) transmissions, respectively. It has been shown in [6] that the WPCN suffers from a so-called “doubly near-far” problem, which occurs when a far user from the H-AP receives less wireless energy than a near user in the DL, but needs to transmit with more power in the UL for achieving

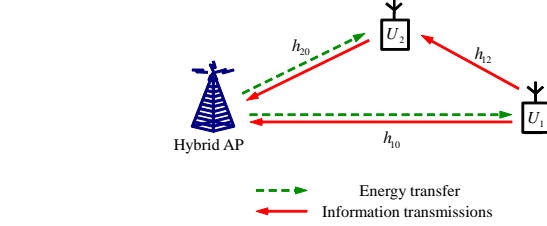


Fig. 1. A two-user wireless powered communication network (WPCN) with DL WET and UL WIT via user cooperation.

the same communication performance due to the distance-dependent signal attenuation in both the DL and UL. As a result, unfair rate allocations among the users are incurred when the sum-throughput of the near and far users is maximized. In [6], we have proposed to assign different time to the near and far users in their UL WIT to solve the doubly near-far problem, which is shown to achieve fair rate allocations among the users in a WPCN.

On the other hand, user cooperation is an effective way to improve the capacity, coverage, and diversity performance in conventional wireless communication systems. Assuming constant energy supplies at user terminals, cooperative communication has been thoroughly investigated in the literature under various protocols such as decode-and-forward and amplify-and-forward (see e.g., [7], [8] and the references therein). Recently, cooperative communication has been studied in energy harvesting wireless communication and SWIPT systems in e.g. [9] and [10], respectively. However, how to exploit user cooperation in the WPCN to overcome the doubly near-far problem and further improve the network throughput and user fairness still remains unknown, which motivates this work.

In this paper, we study user cooperation in the WPCN for throughput optimization. For the purpose of exposition, we consider a two-user WPCN, as shown in Fig. 1, where one H-AP broadcasts wireless energy to two distributed users with different distances in the DL, and the two users transmit their independent information using individually harvested energy to the H-AP in the UL through time-division-multiple-access (TDMA). To enable user cooperation, we propose that the near user which has a better channel than the far user for both DL WET and UL WIT uses part of its allocated UL time and DL harvested energy to first help to relay the information of the far user to the H-AP and then uses the remaining time and energy to transmit its own information. Under this

protocol, we characterize the maximum weighted sum-rate (WSR) of the two users by jointly optimizing the time and power allocations in the network for both WET in the DL and WIT in the UL, subject to the given total time constraint. The achievable throughput gain in the WPCN by the proposed user cooperation scheme is shown both analytically and through simulations over the baseline scheme in [6] without user cooperation.

The rest of this paper is organized as follows. Section II presents the system model of the WPCN with user cooperation. Section III presents the time and power allocation problem to maximize the WSR in the WPCN, and compares the solutions and achievable throughput regions with versus without user cooperation. Section IV presents more simulation results under practical fading channel setups. Finally, Section V concludes the paper.

II. SYSTEM MODEL

As shown in Fig. 1, this paper considers a two-user WPCN with WET in the DL and WIT in the UL. The network consists of one hybrid access point (H-AP) and two users (e.g., sensors) denoted by U_1 and U_2 , respectively, operating over the same frequency band. The H-AP and the users are assumed to be each equipped with one antenna. Furthermore, it is assumed that the H-AP has a constant energy supply (e.g., battery), whereas U_1 and U_2 need to replenish energy from the received signals broadcast by the H-AP in the DL, which is then stored and used to maintain their operations (e.g., sensing and data processing) and also communicate with the H-AP in the UL.

We assume without loss of generality that U_2 is nearer to the H-AP than U_1 , and hence denote the distance between the H-AP and U_1 , that between the H-AP and U_2 , and that between the U_1 and U_2 as D_{10} , D_{20} , and D_{12} , respectively, with $D_{10} \geq D_{20}$. We also assume that $D_{12} \leq D_{10}$ so that U_2 can more conveniently decode the information sent by U_1 than the H-AP, to motivate the proposed user cooperation to be introduced next. Assuming that the channel reciprocity holds between the DL and UL, then the DL channel from the H-AP to user U_i and the corresponding reversed UL channel are both denoted by a complex random variable \tilde{h}_{i0} with channel power gain $h_{i0} = |\tilde{h}_{i0}|^2$, $i = 1, 2$, which in general should take into account the distance-dependent signal attenuation and long-term shadowing as well as the short-term fading. In addition, the channel from U_1 to U_2 is denoted by a complex random variable \tilde{h}_{12} with channel power gain $h_{12} = |\tilde{h}_{12}|^2$. If only the distance-dependent signal attenuation is considered, we should have $h_{10} \leq h_{12}$ and $h_{10} \leq h_{20}$ due to the assumptions of $D_{10} \geq D_{20}$ and $D_{10} \geq D_{12}$. Furthermore, we consider block-based transmissions over quasi-static flat-fading channels, where h_{10} , h_{20} , and h_{12} are assumed to remain constant during each block transmission time, denoted by T , but can vary from one block to another. In each block, it is further assumed that the H-AP has the perfect knowledge of h_{10} , h_{20} , and h_{12} , and U_2 knows perfectly h_{12} .

We propose to employ a harvest-then-transmit protocol similar to that in [6] for the two-user WPCN with user

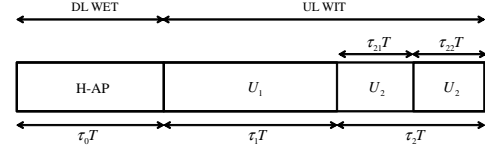


Fig. 2. Transmission protocol for WPCN with user cooperation.

cooperation, as shown in Fig. 2. In each block, during the first $\tau_0 T$ amount of time, $0 < \tau_0 < 1$, the H-AP broadcasts wireless energy to both U_1 and U_2 in the DL with fixed transmit power P_0 . The far user U_1 then transmits its information with average power P_1 during the subsequent $\tau_1 T$ amount of time in the UL, $0 < \tau_1 < 1$, using its harvested energy, and both the H-AP and U_2 decode the received signal from U_1 . To overcome the doubly near-far problem [6], during the remaining $(1 - \tau_0 - \tau_1)T$ amount of time in each block, the near user U_2 first relays the far user U_1 's information and then transmits its own information to the H-AP using its harvested energy with average power P_{21} over $\tau_{21} T$ amount of time and with average power P_{22} over $\tau_{22} T$ amount of time, respectively, where $\tau_{21} + \tau_{22} = \tau_2$. Note that we have a total time constraint given by

$$\sum_{i=0}^2 \tau_i = \tau_0 + \tau_1 + \tau_{21} + \tau_{22} \leq 1. \quad (1)$$

For convenience, we normalize $T = 1$ in the sequel without loss of generality.

During the DL phase, the transmitted complex baseband signal of the H-AP in one block of interest is denoted by an arbitrary random signal, x_0 , satisfying $\mathbb{E}[|x_0|^2] = P_0$. The received signal at U_i , $i = 1, 2$, is then expressed as

$$y_i^{(0)} = \sqrt{h_{i0}} x_0 + z_i, \quad i = 1, 2, \quad (2)$$

where $y_r^{(k)}$ denotes the received signal at U_r during τ_k , with $k \in \{0, 1, 21, 22\}$ and $r \in \{0, 1, 2\}$ (with U_0 denoting the H-AP here). In (2), z_i denotes the received noise at U_i which is assumed to be $z_i \sim \mathcal{CN}(0, \sigma_i^2)$, $i = 1, 2$, where $\mathcal{CN}(\mu, \sigma^2)$ stands for a circularly symmetric complex Gaussian (CSCG) random variable with mean μ and variance σ^2 . It is assumed that P_0 is sufficiently large such that the energy harvested due to the receiver noise is negligible and thus is ignored. Hence, the amount of energy harvested by each user in the DL can be expressed as (assuming unit block time, i.e., $T = 1$)

$$E_i = \zeta_i P_0 h_{i0} \tau_0, \quad i = 1, 2, \quad (3)$$

where $0 < \zeta_i < 1$, $i = 1, 2$, is the energy conversion efficiency at the receiver of U_i .

After the DL phase, each user uses a fixed portion of its harvested energy, denoted by η_i , with $0 < \eta_i \leq 1$, $i = 1, 2$, for the UL WIT, i.e., transmitting own information (by both U_1 and U_2) or relaying the other user's information (by U_2 only) to the H-AP. Within the first τ_1 amount of time allocated to U_1 , the average transmit power of U_1 is given by

$$P_1 = \frac{\eta_1 E_1}{\tau_1} = \eta_1 \zeta_1 P_0 h_{10} \frac{\tau_0}{\tau_1}. \quad (4)$$

We denote x_1 as the complex baseband signal transmitted by U_1 with power P_1 , which is assumed to be Gaussian, i.e., $x_1 \sim \mathcal{CN}(0, P_1)$. The received signals at the H-AP and U_2 in this UL slot for U_1 are expressed, respectively, as

$$y_i^{(1)} = \sqrt{h_{1i}} x_1 + z_i, \quad i = 0, 2, \quad (5)$$

where $z_0 \sim \mathcal{CN}(0, \sigma_0^2)$ denotes the receiver noise at the H-AP.

During the last τ_2 amount of time allocated to U_2 , the total energy consumed by U_2 for transmitting its own information and relaying the decoded information for U_1 should be no larger than $\eta_2 E_2$, i.e.,

$$\tau_{21} P_{21} + \tau_{22} P_{22} \leq \eta_2 \zeta_2 P_0 h_{20} \tau_0. \quad (6)$$

We denote the complex basedband signals transmitted by U_2 for relaying U_1 's information and transmitting its own information as x_{21} with power P_{21} and x_{22} with power P_{22} , respectively, where $x_{21} \sim \mathcal{CN}(0, P_{21})$ and $x_{22} \sim \mathcal{CN}(0, P_{22})$. During τ_{21} and τ_{22} amount of time allocated to U_2 , the corresponding received signals at the H-AP can be expressed as

$$y_0^{(2i)} = \sqrt{h_{20}} x_{2i} + z_0, \quad i = 1, 2. \quad (7)$$

Denote the time allocations to DL WET and UL WIT as $\tau = [\tau_0, \tau_1, \tau_{21}, \tau_{22}]$, and the transmit power values of U_1 and U_2 for UL WIT as $\mathbf{P} = [P_1, P_{21}, P_{22}]$. From [8], the achievable rate of U_1 for a given pair of τ and \mathbf{P} can be expressed from (5) and (7) as

$$R_1(\tau, \mathbf{P}) = \min \left[R_1^{(10)}(\tau, \mathbf{P}) + R_1^{(20)}(\tau, \mathbf{P}), R_1^{(12)}(\tau, \mathbf{P}) \right], \quad (8)$$

with $R_1^{(10)}(\tau, \mathbf{P})$, $R_1^{(20)}(\tau, \mathbf{P})$, and $R_1^{(12)}(\tau, \mathbf{P})$ denoting the achievable rates of the transmissions from U_1 to the H-AP, from U_2 to the H-AP, and from U_1 to U_2 , respectively, which are given by

$$R_1^{(10)}(\tau, \mathbf{P}) = \tau_1 \log_2 \left(1 + \frac{P_1 h_{10}}{\sigma_0^2} \right), \quad (9)$$

$$R_1^{(12)}(\tau, \mathbf{P}) = \tau_1 \log_2 \left(1 + \frac{P_1 h_{12}}{\sigma_2^2} \right), \quad (10)$$

$$R_1^{(20)}(\tau, \mathbf{P}) = \tau_{21} \log_2 \left(1 + \frac{P_{21} h_{20}}{\sigma_0^2} \right). \quad (11)$$

Furthermore, the achievable rate of U_2 is expressed from (7) as

$$R_2(\tau, \mathbf{P}) = \tau_{22} \log_2 \left(1 + \frac{P_{22} h_{20}}{\sigma_0^2} \right). \quad (12)$$

III. OPTIMAL TIME AND POWER ALLOCATIONS IN WPCN WITH USER COOPERATION

In this section, we study the joint optimization of the time allocated to the H-AP, U_1 , and U_2 , i.e., τ , and power allocations of the users, i.e., \mathbf{P} , to maximize the weighted sum-rate (WSR) of the two users. Let $\omega = [\omega_1, \omega_2]$ with ω_1 and ω_2 denoting the given non-negative rate weights for U_1

and U_2 , respectively. The WSR maximization problem is then formulated from (8)-(12) as

$$(P1): \quad \max_{\tau, \mathbf{P}} \quad \omega_1 R_1(\tau, \mathbf{P}) + \omega_2 R_2(\tau, \mathbf{P})$$

$$\text{s.t.} \quad (1), (4), \text{ and } (6),$$

$$\tau_0 \geq 0, \quad \tau_1 \geq 0, \quad \tau_{21} \geq 0, \quad \tau_{22} \geq 0,$$

$$P_1 \geq 0, \quad P_{21} \geq 0, \quad P_{22} \geq 0.$$

Notice that if we set $\tau_{21} = 0$ and $P_{21} = 0$, then (P1) reduces to the special case of WPCN without user cooperation studied in [6], i.e., the near user U_2 only transmits its own information to the H-AP, but does not help the far user U_1 for relaying its information to the H-AP.

Note that (P1) can be shown to be non-convex in the above form. To make this problem convex, we change the variables as $t_{21} = \frac{\tau_{21} P_{21}}{\eta_2 \zeta_2 h_{20} P_0}$ and $t_{22} = \frac{\tau_{22} P_{22}}{\eta_2 \zeta_2 h_{20} P_0}$. Since $P_1 = \eta_1 \zeta_1 P_0 h_{10} \frac{\tau_0}{\tau_1}$ as given in (4), $R_1^{(10)}(\tau, \mathbf{P})$, $R_1^{(12)}(\tau, \mathbf{P})$, $R_1^{(20)}(\tau, \mathbf{P})$, and $R_2(\tau, \mathbf{P})$ in (9)-(12) can be re-expressed as functions of $\mathbf{t} = [\tau, t_{21}, t_{22}]$, i.e.,

$$R_1^{(10)}(\mathbf{t}) = \tau_1 \log_2 \left(1 + \rho_1^{(10)} \frac{\tau_0}{\tau_1} \right), \quad (13)$$

$$R_1^{(12)}(\mathbf{t}) = \tau_1 \log_2 \left(1 + \rho_1^{(12)} \frac{\tau_0}{\tau_1} \right), \quad (14)$$

$$R_1^{(20)}(\mathbf{t}) = \tau_{21} \log_2 \left(1 + \rho_2 \frac{t_{21}}{\tau_{21}} \right), \quad (15)$$

$$R_2(\mathbf{t}) = \tau_{22} \log_2 \left(1 + \rho_2 \frac{t_{22}}{\tau_{22}} \right), \quad (16)$$

where $\rho_1^{(10)} = h_{10}^2 \frac{\eta_1 \zeta_1 P_0}{\sigma_0^2}$, $\rho_1^{(12)} = h_{10} h_{12} \frac{\eta_1 \zeta_1 P_0}{\sigma_2^2}$, and $\rho_2 = h_{20}^2 \frac{\eta_2 \zeta_2 P_0}{\sigma_0^2}$. Furthermore, we introduce a new variable \bar{R} defined as $\bar{R} = \min [R_1^{(10)}(\mathbf{t}) + R_1^{(20)}(\mathbf{t}), R_1^{(12)}(\mathbf{t})]$. It then follows that $\bar{R} \leq R_1^{(10)}(\mathbf{t}) + R_1^{(20)}(\mathbf{t})$ and $\bar{R} \leq R_1^{(12)}(\mathbf{t})$. Accordingly, (P1) can be equivalently reformulated as

$$(P2): \quad \max_{\bar{R}, \mathbf{t}} \quad \omega_1 \bar{R} + \omega_2 R_2(\mathbf{t}) \quad (17)$$

$$\text{s.t.} \quad \tau_0 + \tau_1 + \tau_{21} + \tau_{22} \leq 1, \quad (18)$$

$$t_{21} + t_{22} \leq \tau_0, \quad (19)$$

$$\bar{R} \leq R_1^{(10)}(\mathbf{t}) + R_1^{(20)}(\mathbf{t}), \quad (20)$$

$$\bar{R} \leq R_1^{(12)}(\mathbf{t}), \quad (21)$$

where the time constraint (19) can be shown to be equivalent to the power constraint originally given in (6). It is worth noting that t_{21} and t_{22} denote the amount of time in the DL slot duration τ_0 in which the harvested energy by U_2 is later allocated to relay U_1 's information and transmit its own information in the UL, respectively. By introducing the new variables t_{21} and t_{22} in \mathbf{t} and \bar{R} , joint time and power allocation in problem (P1) is converted to time allocation only in problem (P2).

Note that $R_1^{(10)}(\mathbf{t})$, $R_1^{(20)}(\mathbf{t})$, $R_1^{(12)}(\mathbf{t})$, and $R_2(\mathbf{t})$ are all monotonically increasing functions over each element of (τ_0, τ_1) , (τ_0, τ_1) , (t_{21}, τ_{21}) , and (t_{22}, τ_{22}) , respectively. Let the optimal solution of (P2) be denoted by $\mathbf{t}^* = [\tau^*, t_{21}^*, t_{22}^*] = [\tau_0^*, \tau_1^*, \tau_{21}^*, \tau_{22}^*, t_{21}^*, t_{22}^*]$. Then, it can be easily verified that $t_{21}^* + t_{22}^* = \tau_0^*$ must hold (otherwise, we can always increase $R_2(\mathbf{t})$ by increasing t_{22} to improve the weighted sum-rate). Similarly, it can also be verified that

$$R_1^{(10)}(\mathbf{t}^*) + R_1^{(20)}(\mathbf{t}^*) \leq R_1^{(12)}(\mathbf{t}^*), \quad (22)$$

since, otherwise, we can allocate part of τ_{21} (or t_{21}) to τ_{22} (or t_{22}) until the equality holds, which will result in an increased $R_2(\tau, \mathbf{t})$ without reducing $R_1(\tau, \mathbf{t})$.

Lemma 3.1: $R_1^{(10)}(\mathbf{t})$, $R_1^{(12)}(\mathbf{t})$, $R_1^{(20)}(\mathbf{t})$, and $R_2(\mathbf{t})$ are all concave functions of \mathbf{t} .

Proof: Due to the space limitation, the proof is omitted here, and is given in a longer version of this paper available online [11]. ■

From Lemma 3.1, it follows that the objective function of (P2) is a concave function of \mathbf{t} , and so are functions at the right-hand side of both (20) and (21). Furthermore, the constraints in (18) and (19) are both affine. Therefore, problem (P2) is a convex optimization problem, and furthermore it can be verified that (P2) satisfies the Slater's condition [12]; hence, it can be solved by the Lagrange duality method, shown as follows. From (17)-(21), the Lagrangian of (P2) is given by

$$\begin{aligned} \mathcal{L}(\bar{R}, \mathbf{t}, \boldsymbol{\lambda}) = & \omega_1 \bar{R} + \omega_2 R_2(\mathbf{t}) \\ & - \lambda_1 (\tau_0 + \tau_1 + \tau_{21} + \tau_{22} - 1) - \lambda_2 (t_{21} + t_{22} - \tau_0) \\ & - \lambda_3 (\bar{R} - R_1^{(10)}(\mathbf{t}) - R_1^{(20)}(\mathbf{t})) - \lambda_4 (\bar{R} - R_1^{(12)}(\mathbf{t})), \end{aligned} \quad (23)$$

where $\boldsymbol{\lambda} = [\lambda_1, \lambda_2, \lambda_3, \lambda_4]$ denote the Lagrange multipliers associated with the constraints in (18), (19), (20), and (21), respectively. Notice that $\lambda_3 + \lambda_4 \geq \omega_1$ must hold; otherwise, the Lagrangian will go unbounded from above with $\bar{R} \rightarrow \infty$. The dual function of problem (P2) is then given by

$$\mathcal{G}(\boldsymbol{\lambda}) = \max_{\mathbf{t} \in \mathcal{D}, \bar{R} \geq 0} \mathcal{L}(\bar{R}, \mathbf{t}, \boldsymbol{\lambda}), \quad (24)$$

where \mathcal{D} is the feasible set of \mathbf{t} specified by $t_{21} \geq 0$, $t_{22} \geq 0$, and $\tau \geq 0$ (\geq here denotes the component-wise inequality). The dual problem of (P2) is thus given by $\min_{\lambda \geq 0, \lambda_3 + \lambda_4 \geq \omega_1} \mathcal{G}(\boldsymbol{\lambda})$. The optimal solution \mathbf{t}^* can be obtained if the optimal dual solution $\boldsymbol{\lambda}^*$ is found by solving the dual problem of (P2).

Proposition 3.1: Given positive weights $\omega_1 > 0$ and $\omega_2 > 0$, the optimal solution to (P2), $\mathbf{t}^* = [\tau^*, t_{21}^*, t_{22}^*]$, is given by

$$\tau^* = \left[\frac{(\sqrt{b^2 - 4ac} - b) \tau_1^*}{2a}, \frac{\tau_0^*}{z_1^*}, \frac{\rho_2 t_{21}^*}{z_{21}^*}, \frac{\rho_2 t_{22}^*}{z_{22}^*} \right], \quad (25)$$

$$[t_{21}^*, t_{22}^*] = \left[\left(\frac{\lambda_3^* \tau_{21}^*}{\lambda_2^* \ln 2} - \frac{\tau_{21}^*}{\rho_2} \right)^+, \left(\frac{\omega_2^* \tau_{22}^*}{\lambda_2^* \ln 2} - \frac{\tau_{22}^*}{\rho_2} \right)^+ \right], \quad (26)$$

TABLE I
ALGORITHM TO SOLVE (P1).

1) Initialize $\lambda \geq 0$
2) Repeat
1. Initialize $k = 0$, $\tau = \tau^{(0)}$, $\mathbf{t} = \mathbf{t}^{(0)}$.
2. Repeat
(1) Obtain $[\tau_0^{(k+1)}, t_{21}^{(k+1)}, t_{22}^{(k+1)}]$ from (25) and (26) with given $[\tau_1^{(k)}, \tau_{21}^{(k)}, \tau_{22}^{(k)}]$.
(2) Obtain $[\tau_1^{(k+1)}, \tau_{21}^{(k+1)}, \tau_{22}^{(k+1)}]$ from (25) and (26) with given $[\tau_0^{(k+1)}, t_{21}^{(k+1)}, t_{22}^{(k+1)}]$.
3. until \mathbf{t}^* converges to a predetermined accuracy.
4. Compute $\bar{R}^* = \min [R_1^{(10)}(\mathbf{t}^*) + R_1^{(20)}(\mathbf{t}^*), R_1^{(12)}(\mathbf{t}^*)]$.
5. Update λ subject to $\lambda_3 + \lambda_4 \geq \omega_1$ using the ellipsoid method and the subgradient of $\mathcal{G}(\lambda)$ given by (31)-(34).
3) Until Stopping criteria of the ellipsoid method is met.
4) Set $P_{21}^* = \eta_2 \zeta_2 h_{20} P_0 \frac{t_{21}^*}{\tau_{21}^*}$ and $P_{22}^* = \eta_2 \zeta_2 h_{20} P_0 \frac{t_{22}^*}{\tau_{22}^*}$.

with $(x)^+ \triangleq \max(0, x)$, and $\lambda_1^* > 0$, $\lambda_2^* > 0$, $\lambda_3^* \geq 0$, and $\lambda_4^* \geq 0$ denoting the optimal dual solutions. Moreover, a , b , and c in (25) are given, respectively, by

$$a = (\lambda_1^* - \lambda_2^*) \rho_1^{(10)} \rho_1^{(12)}, \quad (27)$$

$$b = (\lambda_1^* - \lambda_2^*) \left(\rho_1^{(10)} + \rho_1^{(12)} \right) - \omega_1 \rho_1^{(10)} \rho_1^{(12)}, \quad (28)$$

$$c = \lambda_1^* - \lambda_2^* - \lambda_3^* \rho_1^{(10)} - \lambda_4^* \rho_1^{(12)}. \quad (29)$$

Finally, z_1^* , z_{21}^* , and z_{22}^* in (25) are solutions of $\lambda_3^* f(\rho_1^{(10)} z) + \lambda_4^* f(\rho_1^{(12)} z) = \lambda_1^* \ln 2$, $f(z) = \frac{\lambda_1^* \ln 2}{\lambda_3^*}$, and $f(z) = \frac{\lambda_1^* \ln 2}{\omega_2}$, respectively, where

$$f(z) \triangleq \ln(1+z) - \frac{z}{1+z}. \quad (30)$$

Proof: Please refer to [11]. ■

According to Proposition 3.1, we can obtain \mathbf{t}^* as follows. Denote \mathbf{t}^* and \bar{R}^* as the maximizer of $\mathcal{L}(\bar{R}, \mathbf{t}, \boldsymbol{\lambda})$ in (23) for a given $\boldsymbol{\lambda}$. We can first obtain \mathbf{t}^* by iteratively optimizing between $[\tau_0, t_{21}, t_{22}]$ and $[\tau_1, \tau_{21}, \tau_{22}]$ using (25) and (26) with one of them being fixed at one time until they both converge. Then we compute $\bar{R}^* = \min [R_1^{(10)}(\mathbf{t}^*) + R_1^{(20)}(\mathbf{t}^*), R_1^{(12)}(\mathbf{t}^*)]$. With $\mathcal{G}(\boldsymbol{\lambda})$ obtained for each given $\boldsymbol{\lambda}$, the optimal $\boldsymbol{\lambda}^*$ minimizing $\mathcal{G}(\boldsymbol{\lambda})$ can then be found by updating $\boldsymbol{\lambda}$ using sub-gradient based algorithms, e.g., the ellipsoid method [13], with the sub-gradient of $\mathcal{G}(\boldsymbol{\lambda})$, denoted as $\boldsymbol{\nu} = [\nu_1, \nu_2, \nu_3, \nu_4]$, given by

$$\nu_1 = \tau_0^* + \tau_1^* + \tau_{21}^* + \tau_{22}^* - 1, \quad (31)$$

$$\nu_2 = t_{21}^* + t_{22}^* - \tau_0^*, \quad (32)$$

$$\nu_3 = \bar{R}^* - R_1^{(10)}(\mathbf{t}^*) + R_1^{(20)}(\mathbf{t}^*), \quad (33)$$

$$\nu_4 = \bar{R}^* - R_1^{(12)}(\mathbf{t}^*). \quad (34)$$

Once $\boldsymbol{\lambda}^*$ and the corresponding $\mathbf{t}^* = \mathbf{t}^*$ are obtained, the optimal power allocation solution at U_2 for (P1) is obtained as $P_{21}^* = \eta_2 \zeta_2 h_{20} P_0 \frac{t_{21}^*}{\tau_{21}^*}$ and $P_{22}^* = \eta_2 \zeta_2 h_{20} P_0 \frac{t_{22}^*}{\tau_{22}^*}$. To summarize, one algorithm to solve problem (P1) is given in Table I.

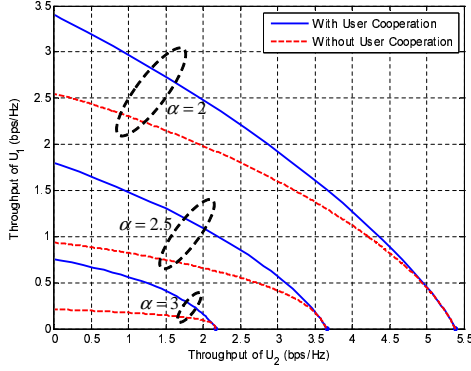


Fig. 3. Throughput region comparison for WPCN with versus without user cooperation.

Fig. 3 shows the achievable throughput regions of the two-user WPCN with user cooperation by solving (P1) with different user rate weights as compared to that by the baseline scheme in [6] without user cooperation, for different values of path-loss exponent, α . It is assumed that $D_{10} = 10\text{m}$, and $D_{12} = D_{20} = 5\text{m}$. The channel power gains in the network are modeled as $h_{ij} = 10^{-3}\theta_{ij}D_{ij}^{-\alpha}$, $ij \in \{10, 20, 12\}$, for distance D_{ij} in meter, with the same path-loss exponent α and 30dB signal power attenuation for both users at a reference distance of 1m, where θ_{ij} represents the additional channel short-term fading. We ignore the effects of short-term fading in this case by setting $\theta_{10} = \theta_{20} = \theta_{12} = 1$, to focus on the effect of the doubly near-far problem due to distance-dependent attenuation only. Moreover, it is assumed that $P_0 = 30\text{dBm}$ and the bandwidth is 1MHz. The AWGN at the receivers of the H-AP and U_2 is assumed to have a white power spectral density of -160dBm/Hz . For each user, it is assumed that $\eta_1 = \eta_2 = 0.5$, $\zeta_1 = \zeta_2 = 0.5$, and $\Gamma = 9.8$ assuming that uncoded quadrature amplitude modulation (QAM) is employed with a target bit-error rate (BER) of 10^{-7} [14].

From Fig. 3, it is observed that the throughput region of WPCN with user cooperation is always larger than that without user cooperation, which is expected as the latter case only corresponds to a suboptimal solution of (P1) in general. Denote $\delta = R_{1,\max}^{(wc)}/R_{1,\max}^{(nc)}$ with $R_{1,\max}^{(wc)}$ and $R_{1,\max}^{(nc)}$ denoting the maximum achievable throughput of the far user U_1 in the WPCN with and without user cooperation, respectively. It is then inferred from Fig. 3 that $\delta = 1.33, 1.92$, and 3.60 when $\alpha = 2, 2.5$, and 3 , respectively, which implies that user cooperation in the WPCN is more beneficial in improving the far user's rate as α increases, i.e., when the doubly near-far problem is more severe. This is because the achievable rate for the direct link from U_1 to the H-AP decreases more significantly than that of the other two links with increasing α .

Next, Fig. 4 compares the achievable throughput regions of WPCN with versus without user cooperation with $\alpha = 2$. In this case, the H-AP and the two users are assumed to lie on a straight line with $D_{20} = \kappa D_{10}$ and $D_{12} = (1 - \kappa)D_{10}$,

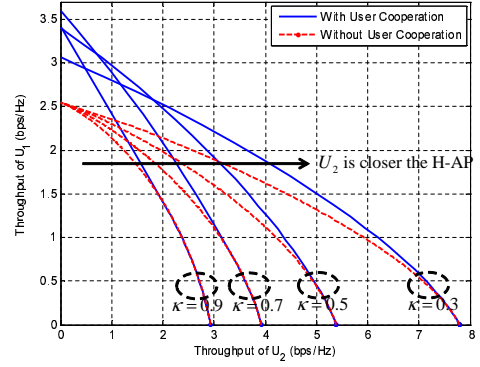


Fig. 4. Throughput region comparison for WPCN with versus without user cooperation with $\alpha = 2$.

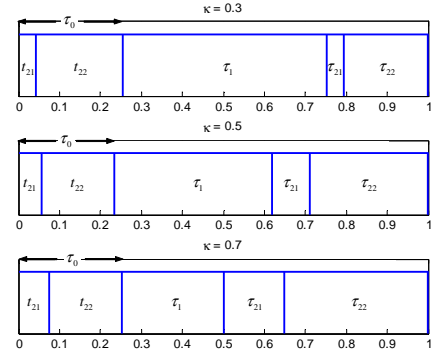


Fig. 5. Optimal time allocations in \mathbf{t}^* for different values of κ when $\alpha = 2$ and $R_1(\mathbf{t}^*) = R_2(\mathbf{t}^*)$.

$0 < \kappa < 1$. It is observed that when κ is not large (i.e., $\kappa \leq 0.7$), $R_{1,\max}^{(wc)}$ decreases with decreasing κ . This is because when the near user U_2 moves more away from the far user U_1 (and thus closer to the H-AP), the degradation of $R_1^{(12)}(\mathbf{t}^*)$ for the U_1 -to- U_2 link with decreasing κ is more significant than the improvement in $R_1^{(20)}(\mathbf{t}^*)$ of the U_2 -to-H-AP link since $R_1^{(10)}(\mathbf{t}^*) + R_1^{(20)}(\mathbf{t}^*) \leq R_1^{(12)}(\mathbf{t}^*)$ with the optimal time allocations \mathbf{t}^* . On the other hand, when κ is larger than a certain threshold (e.g., $\kappa = 0.9$), $R_{1,\max}^{(wc)}$ decreases with increasing κ since in this case not only the far user U_1 , but also the relatively nearer user U_2 suffers from the significant signal attenuation from/to the H-AP.

Finally, Fig. 5 shows the optimal time allocations in \mathbf{t}^* for (P2) when $R_1(\mathbf{t}^*) = R_2(\mathbf{t}^*)$, i.e., the common-throughput [6] is maximized,¹ with $\alpha = 2$ and $\kappa = 0.3, 0.5, 0.7$. It is observed that τ_1^* decreases but both τ_{21}^* and τ_{22}^* increase with increasing κ . This is because when the near user U_2 moves more away from the H-AP, U_2 suffers from more severe signal attenuation as κ increases, and thus it is necessary to allocate more time to U_2 for both transmitting own information and relaying information for U_1 in order to maximize the common

¹The common-throughput can be obtained by searching over ω , for which one algorithm is provided in [6].

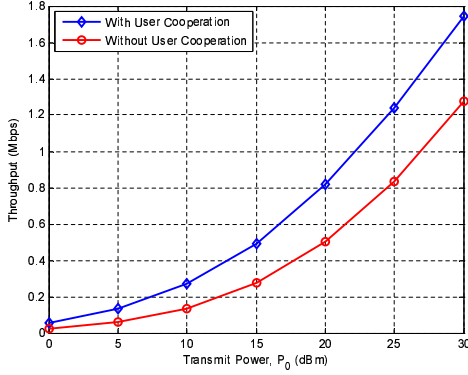


Fig. 6. Maximum common-throughput versus P_0 with $\alpha = 2$ and $\kappa = 0.5$.

throughput with $R_1(\mathbf{t}^*) = R_2(\mathbf{t}^*)$.

IV. SIMULATION RESULT

In this section, we compare the maximum common throughput in the WPCN with versus without user cooperation under the practical fading channel setup, while the other system parameters are set similarly as for Figs. 3 and 4. The short-term fading in the network is assumed to be Rayleigh distributed, and thus θ_{10} , θ_{20} , and θ_{12} in the previously given channel models are exponentially distributed with unit mean.

Fig. 6 shows the maximum average common-throughput versus the transmit power of H-AP, i.e., P_0 in dBm, with $\alpha = 2$ and $\kappa = 0.5$. It is observed that the maximum common-throughput in the WPCN with user cooperation is notably larger than that without user cooperation, especially when P_0 becomes large. This result shows the effectiveness of the proposed user cooperation in the WPCN to further improve both the throughput and user fairness as compared to the baseline scheme in [6] with optimized time allocation only but without user cooperation.

Fig. 7 shows the maximum average common-throughput versus different values of κ with $P_0 = 30$ dBm. It is observed that the maximum common-throughput in the WPCN with user cooperation is always larger than that without user cooperation. Furthermore, the common-throughput in the WPCN with user cooperation first increases with κ , but decreases with increasing κ when κ is larger than a certain threshold. The threshold value of κ that maximizes the average common-throughput of the WPCN with user cooperation is observed to increase with α .

V. CONCLUSION

This paper studied a two-user WPCN in which user cooperation is jointly exploited with resources (time, power) allocation to maximize the network throughput and yet achieve desired user fairness by overcoming the doubly near-far problem. We characterized the maximum WSR in the WPCN with user cooperation via a problem reformulation and applying the tools from convex optimization. By comparing the achievable throughput regions as well as the maximum common-throughput in the WPCN with versus without user cooperation,

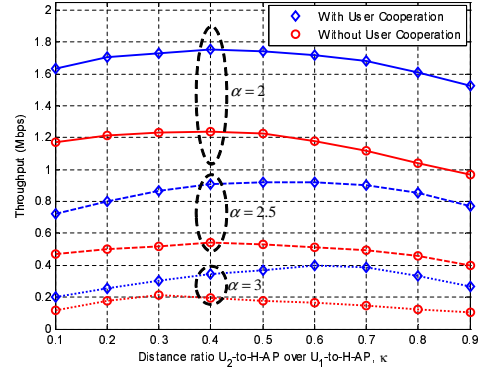


Fig. 7. Maximum common-throughput versus κ with $P_0 = 30$ dBm and $\alpha = 2, 2.5, 3$.

it is shown by extensive simulations that the proposed user cooperation is effective to improve both the throughput and user fairness. In future work, we will extend the results of this paper to other setups, e.g., when there are more than two users, alternative relaying schemes are applied, and/or other performance metric is considered.

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